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AEROSPACE POST-PROCESSING AND VISUALIZATION LAB

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Contents

Abstract/Summary

This report summarizes a Defense University Research Investment Program (DURIP) project involving creation of an *Aerospace Post-Processing and Visualization Lab* (APVL) in the School of Aeronautics and Astronautics at Purdue University. Even though the entire facility has been in place for about eight months, it has had a dramatic impact on the capabilities of our department to visualize complex three-dimensional and/or time-dependent data from both experiments and computations. Innovative post-processing schemes have already been developed using the hardware and software purchased through this grant. In fact, the facility is so heavily used, that the department has augmented its capabilities by purchasing additional workstations for the lab.

Specific DoD projects which have been impacted by the funds include: research in liquid jet atomization processes, high-speed boundary layer transition, and materials degradation and fatigue. In addition, the lab has positively impacted turbulence research germane to the interests of DoD. Thus far, the APVL has been utilized by 7 faculty and 24 graduate students within our department.

This report summarizes some of the major developments made possible by the DURIP funds. Innovative approaches to the visualization of liquid jet atomization processes have been developed. Collaboration on the visualization of large, three-dimensional, time-dependent turbulent flow fields directly from parallel computers has been started. Additional impacts on the visualization of heat-treatment processes, and in boundary layer transition experiments are also described herein.

1 Overview

Because of the anticipated usage of the *Aerospace Post-Processing and Visualization Lab*, it was decided to place the facility in a fairly large room (Grissom 356) capable of also housing up to 13 graduate students involved with high-performance computing. Figure 1 provides a general layout of the facility in its current form. The arrangement provides a common area for use of the visualization tools in addition to office space for the students. While we originally budgeted much more space than that required for the DURIP equipment, the augmentation of this facility using additional departmental funds has effectively utilized the remaining space. As mentioned previously, the facility is under nearly-continuous use for a large portion of the day and into the evening hours. The usage of the equipment has exceeded our expectations, due to its unique capabilities to display and print (to video tape, transparency, or paper) graphical data.

Table 1 provides a description of the current hardware in use within the *Aerospace Post-Processing and Visualization Lab*. The two Silicon Graphics Indigo 2 Extreme machines provide the main graphics engines for display and post processing of large datasets. These machines offer some of the fastest graphics available in today's marketplace and provide a means to handle even the largest three-dimensional, time-dependent data from turbulence modeling. Recently, the ability to perform large computations has been enhanced through the addition of an IBM R6000 machine which is capable of efficiently handling a wide variety of finite element and computational fluid dynamic calculations. This machine was purchased from gift funds provided by *The Boeing Company* at a substantial discount offered by IBM.

Two smaller Silicon Graphics INDY workstations provide a means for students with modest datasets to display graphical information in an efficient manner. In order to provide access for students with experimental data, it was decided to locate one of the machines (as well as a Laserwriter printer to preview images) within the Aerospace Sciences Lab located at the Purdue Airport. These machines were also purchased (in part) through the use of gift funds from *The Boeing Company*. High resolution hard copies or transparencies can be generated using the Tectronix printer.

The Galileo Video Package provides a broadcast-quality capability to download graphical results to high-resolution video tape. Titles, subtitles, and sound can be added on a frame-by-frame basis using this hardware (and associated software). In addition, portions of video tape can be digitally-captured using the Galileo Video Package. Finally, a high-quality VCR and 13 inch color monitor complete the lab. The VCR provides the interface with video tapes, and the monitor can be used to interrogate the quality of video clips downloaded from the workstations.

The total cost for the items delineated in Table 1 is $103,487. Several expenditures for cables, brackets, ethernet connections, labor, etc., are not included in Table 1 and can be found in the Fiscal Report associated with this project. Just from the costs outlined in Table 1, it is obvious that Purdue has augmented its cost sharing of this project substantially (original total costs were $91,226 of which $68449 was provided by DoD and $22,817 was provided by cost sharing).

Table 1: Current Hardware in *Aerospace Post-Processing and Visualization Lab*

Silicon Graphics Indigo 2 Extreme Computer ($31891) R4400 CPU, 128 MB RAM, 2×2 GB Hard Drive
Silicon Graphics Indigo 2 Extreme Computer ($28912) R4400 CPU, 64 MB RAM, 2 GB Hard Drive CD ROM, DAT Tape Drive
IBM RISC R6000 Computer ($12000) Model 580, 128 MB RAM, 4.2 GB Hard Drive
Silicon Graphics INDY Computer ($5246) 133 MHz R4600PC CPU, 32 MB RAM, 535 MB Hard Drive IndyCam External Camera
Silicon Graphics INDY Computer* ($5246) 133 MHz R4600PC CPU, 32 MB RAM, 535 MB Hard Drive IndyCam External Camera
Galileo Video (-601 Digital Video Option) ($7469)
Textronics Phaser II-SX Color Printer ($9415)
Apple Laserwriter 16/600 Postscript Printer* ($2051)
Sony Model SLV-R1000 4 Head VCR ($1257) Sony Trinitron 13 inch Color Monitor

* Located at Aerospace Sciences Lab

Table 2 highlights the DoD-Sponsored research projects currently under investigation within the *Aerospace Post-Processing and Visualization Lab*. Three of the four projects discussed in the original proposal (Liquid Jet Atomization, Materials Degradation and Fatigue, and Boundary Layer Transition) involve both experimental and computational studies, while the Turbulence Research project is primarily computational in nature. The Turbulence Research project is sponsored by NASA and, therefore, is not included in Table 2. However, the results of this project are also pertinent to DoD goals. Together these projects currently employ 24 graduate students involving 7 faculty within our department.

Through the development of the APVL, these projects have enhanced their capabilities in achieving DoD research goals. In addition, the new computer facilities have enabled the development of several new post-processing strategies aimed at improving the visualization of research results as described in the following sections. Moreover, students having access to this lab are currently gaining valuable training in state-of-the-art computer graphics. The following subsections of this report discuss in detail the significant impact the *Aerospace Post-Processing and Visualization Lab* is having in enhancing the understanding of complex research results in the projects highlighted in Table 2.

Table 2: Projects Currently Utilizing *Aerospace Post-Processing and Visualization Lab*

SPONSOR	PROJECT TITLE	PROJECT PERIOD	P.I.
AFOSR	Materials Degradation and Fatigue in Aerospace Materials	7/1/93-6/30/97	Grandt/Sun/Farris
AFOSR	Modeling of Liquid Jet Atomization Processes	7/1/92-6/30/94	Heister
AFOSR/ASEE	New Approaches for Modeling Liquid Jet Atomization	6/1/93-5/31/96	Heister
AFOSR	Laminar/Turbulent Transition in High Speed Compressible Boundary Layers	11/15/93-11/14/96	Schneider/Collicott
AFOSR	Laminar/Turbulent Transition in High Speed Compressible Boundary Layers	7/1/94-6/30/97	Schneider/Collicott

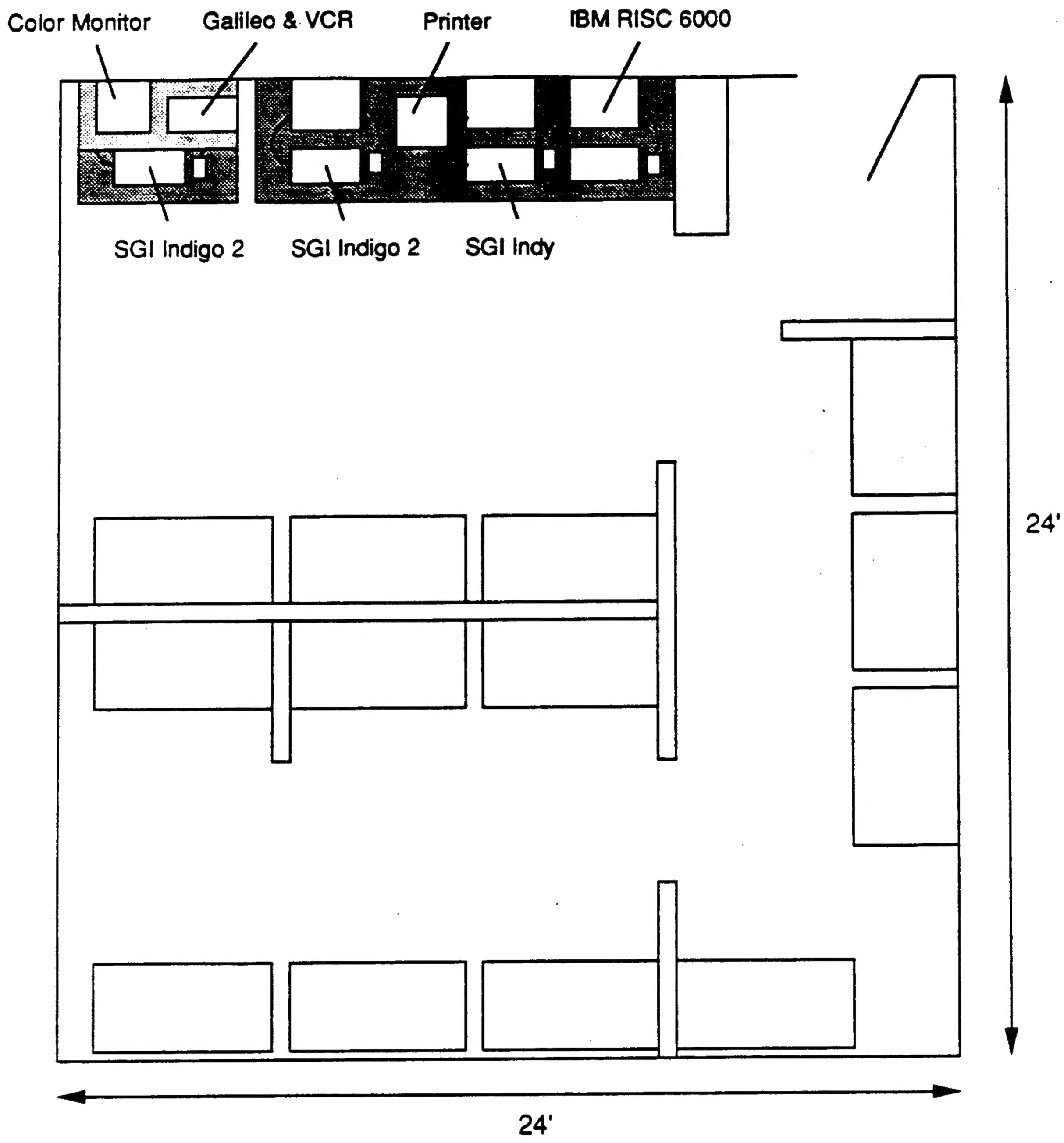


Figure 1: Layout of *Aerospace Post-Processing and Visualization Lab*in Grissom Hall, Room 356

2 Visualization of Jet Atomization Processes

Under the management of Dr. Mitat Birkan of the AFOSR Propulsion Directorate, we are currently working on a project involving the atomization of liquid fuel jets injected into a quiescent gas (AFOSR Contract F49620-92-J-0390). This work includes modeling of the flow both inside and outside the fuel orifice. In addition, experimental efforts are also underway to provide a means of comparison with the models developed under this project. Several numerical models[1–4] have been developed in accordance with the goals of this project. The models are capable of tracing the evolution of the free surface defining the jet boundary with time.

Using the capabilities of *Aerospace Post-Processing and Visualization Lab*, we have been able to significantly enhance our ability to visualize the large amounts of time-dependent data generated by our models. In particular, we have completed development of interfaces required to provide three-dimensional renderings of the jet evolution through the use of public domain software created precisely for this purpose. The software package, *Geomview*[5], is an interactive program for viewing and manipulating geometric objects, written by members of the Geometry Center at The University of Minnesota. The Geometry Center is a mathematics research and education center, funded by the National Science Foundation as part of the Science and Technology Center program. *Geomview* is available for free via anonymous ftp on the Internet from host 'geom.umn.edu'. This program allows multiple independently controllable objects, can handle any number of these objects simultaneously, and allows interactive control of object details such as point of view, speed of movement, and appearance of surfaces and lines.

We have developed a number of external modules which act as interfaces between *Geomview* and our BEM output files. Current BEM codes save boundary locations to a file at user-definable intervals during the program's execution. For an axisymmetric geometry, the external module reads in this file of points on a line, rotates this line around the symmetry axis using a specified number of increments, and defines a retangular mesh in three dimensional space. This mesh is passed to Geomview which is used as a display engine on the Silicon Graphics systems. For data files from a two dimensional solution, the user defines the width of the surface in the third dimension instead of the number of increments in the circumferential direction.

For surfaces with a small number of nodes and frames, our external modules read in the entire BEM data file into memory. A loop in the module updates the mesh in *Geomview*, creating an animation of the surface. For surfaces with large numbers of nodes and frames, the external module reads in the data from disk just before updating the mesh, incurring a penalty in the animation frame rate. Fast frame rates can be obtained using modules which save a snapshot of each surface to disk in SGI RGB format. These images can be imported into the IRIS Movie Maker, creating an SGI movie file. These files can be easily captured to video tape using the Galileo system.

Results of some sample simulations displayed using the *Geomview* software are provided in Fig. 2. These images were printed on our high-resolution Tectronix printer which was purchased under funding associated with this grant. Figure 2a shows a jet

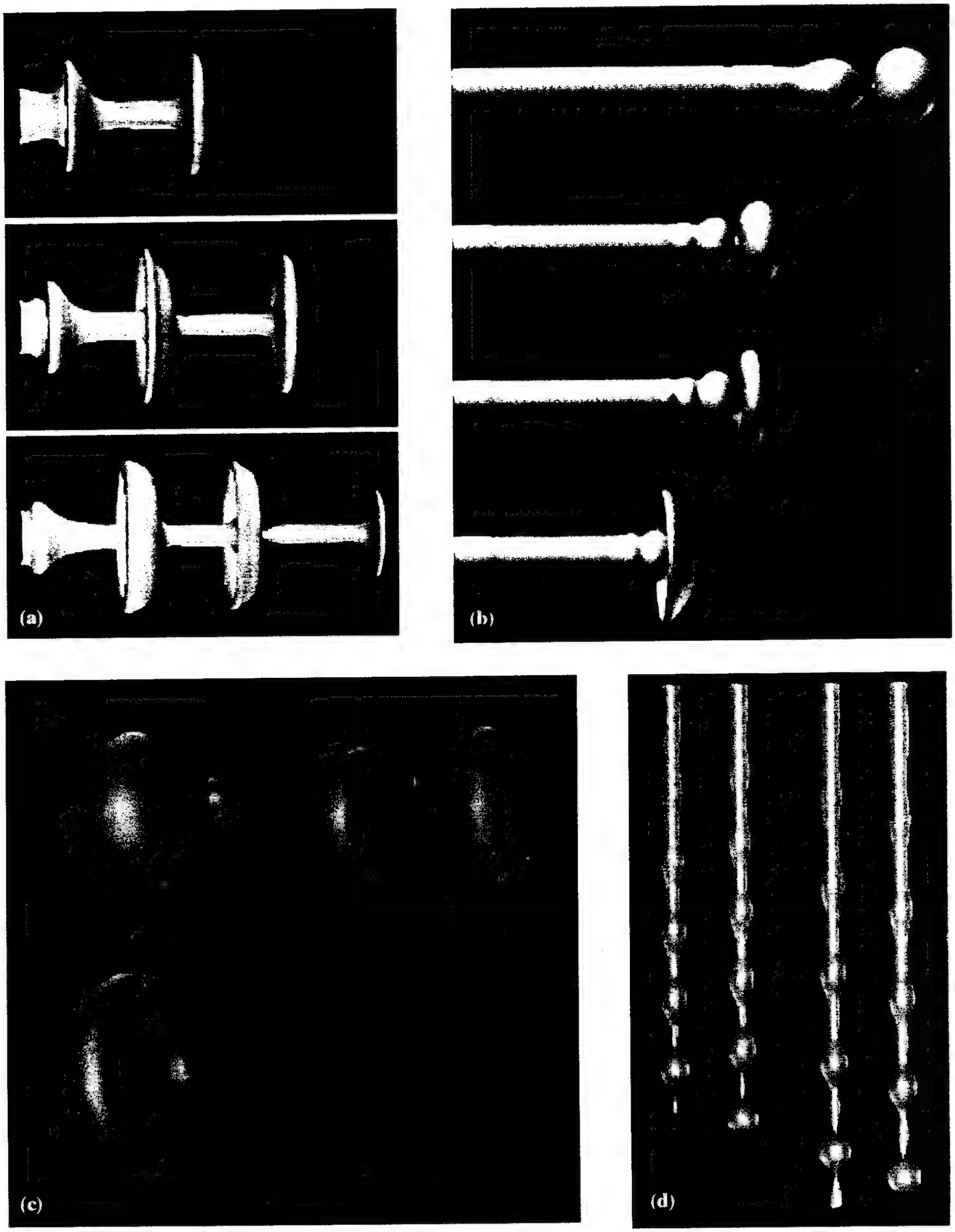


Figure 2. Visualization of Atomization Processes Using Geomveiew.

responding to large sinusoidal pressure oscillations, as might be experienced during a combustion instability in a liquid rocket engine[6]. The injection conditions are at a Weber number of 200. The perturbation is modeled as a 35% sinusoidal variation in injection velocity (about the mean flow) at a dimensionless frequency of 2.0.

Figure 2b presents results of a fully-coupled jet injection simulation[6]. In this case, solutions are obtained for both liquid and gaseous phases. This figure depicts the dramatic influency gas density has on the injection process. The upper profile is for a gas/liquid density ratio of 0.001, followed by simulations at 0.02, 0.03, and 0.05. All these simulations were conducted at a Weber number of 17.6, which can be thought of as a fixed orifice diameter and injection velocity.

Figure 2c provides simulations of atomization of a liquid droplet subjected to acoustic perturbations from the gas[7]. At very low acoustic intensities, the droplet will oscillate, but it will not atomize (simulations not shown). As acoustic intensity is increased, the droplet first atomizes in the "nipple mode" (upper left in Fig. 2c), followed by the "dumbell mode" (upper right). At even higher intensities, breakup occurs in an annulus around the outer periphery of the droplet (lower left and right in Fig. 2c).

Figure 2d presents a simulation of atomization of a low speed jet subjected to small velocity perturbations[8]. On the left, a wave number of 0.5 is depicted, while the shorter waves associated with a wave number of 0.7 are depicted on the right. Note how the column alternatively breaks off large (main) and small (satellite) droplets. The simulations can accurately predict observed droplet sizes for arbitrary unsteady injection conditions within the low-speed jet regime.

While the images shown in Figure 2 give the reader a general idea of the power of the visualization package and hardware purchased under this grant, they do not reveal the information gained by viewing of full time-dependent simulations (either on screen or reproduced on video tape). It is in this area that we have found the tools to be most useful. For example, the movies made with the *Geomview* package have significantly enhanced our understanding of the atomization process. Waves which are created as a result of atomization events are seen to interact with other structures in the jet in a nonlinear fashion leading to very complex waveforms and jet profiles. Droplets can be visualized as they alternatively oscillate in second and fourth mode harmonics. Unsteady injection can be visualized as bulges and valleys which appear near the orifice plane and are convected downstream. It is in these areas where the *Aerospace Post-Processing and Visualization Lab*has provided a pronounced effect on this research. We anticipate further developments of both simulation software and visualization tools in the future.

3 Impact on Turbulence Research

There are two projects of interest to DoD in the area of turbulent flows[9,10] that have made use of the Aerospace Post-Processing and Visualization Lab. The first is the large eddy simulation (LES) of a spatially evolving supersonic boundary layer. This work has been sponsored by the NASA Langley Research Center under grant NAG-1-1509. The goal of this project is to develop LES technology for compressible turbulent flows so that it can ultimately be used for complex-geometry high-Reynolds number applications. Visualizations have been done of the transition process from laminar to turbulent flow. These have helped our understanding of how the turbulence develops from large disturbances introduced through a blowing and suction slot. Visualizations are also helpful in assessing the need for grid refinement in order to capture the vortical structures responsible for turbulence production.

A proposal to extend this work to the study of transition on asymmetric forebody shapes has been submitted to Dr. Len Sakell, manager of the AFOSR External Aerodynamics and Hypersonics program. This project will complement the experimental work being done by Professor Schneider who is a co-PI on the current DURIP grant. In addition to Professor Schneider's use of the APVL, the lab will be a valuable tool in understanding the numerical simulation results of this complex, three-dimensional, time-dependent flow phenomenon.

The second project is the direct numerical simulation (DNS) of an axial vortex, similar to a wing-tip vortex on a large transport aircraft. The goal of this work is to understand the development of turbulence within a vortex and to understand the effects of rotation and strain on the turbulence. Results from the simulations have been used both to gain insight into the physical processes occurring within the turbulent vortex and to evaluate turbulence models that are used in engineering calculations.

A visualization of the axial vortex is shown in figure 3. This shows an isocontour of vorticity magnitude and a color contour plot of vorticity magnitude in a single-plane slice through the vortex. The isocontour of vorticity shows the helical coherent vortical structures that arise out of the random initial disturbance field. The wavelength of the helical structures corresponds closely to that of the most unstable mode of a linear stability analysis. The internal structure of the vortex is revealed in the color contour plot. Such plots have been helpful in identifying regions of the vortex where turbulence is produced and in making comparisons with experimental measurements of Reynolds stresses.

The visualization program used to generate figure 3 is FAST (Flow Analysis Software Toolkit) obtained from NASA. As a NASA contractor this software was available at no cost. This program allows for the interactive investigation of three-dimensional flow fields. It has many features that are of use in fluid mechanics, such as tracing streamlines and vortex lines, calculating scalar fields such as vorticity magnitude, and computing vector fields such as velocity vectors, vorticity vectors and pressure gradients. Additional software obtained from NASA includes a two-dimensional x-y plotting program for making publication quality graphs, an rgb image editing program, and a PostScript editing program.

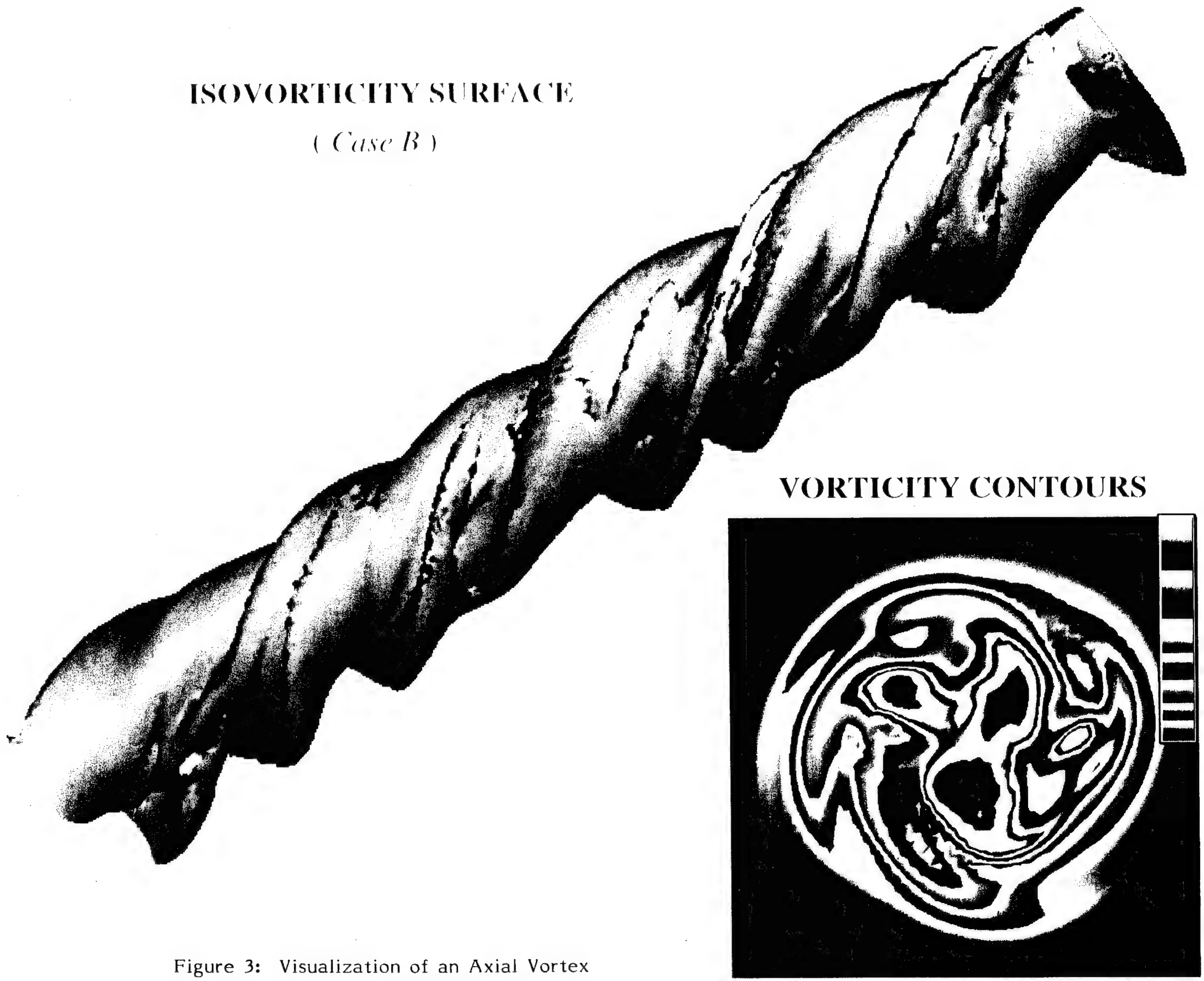


Figure 3: Visualization of an Axial Vortex

The above software tools have proved useful; however, our visualization needs go beyond their capabilities. We would like to study the temporal evolution of the turbulence. For that we need to make animations. However, the size of the flow fields makes that difficult. The vortex depicted in figure 3 uses a grid that has $128 \times 128 \times 256$ points. Simulations of other flows we have done have used grids as large as $256 \times 512 \times 256$ points. It is not feasible to store a large number of these three-dimensional flow fields from which to make an animated sequence. Instead we plan to perform visualizations as the simulations are running. The simulations are performed on a 142-node Intel Paragon parallel processing supercomputer we have at Purdue. We are collaborating with Professor Chandrajit Bajaj of Purdue's School of Computer Science on developing the capability of creating isocontours on the Paragon during the course of the simulation which can then be sent to a workstation for visualization. In this way an animated sequence can be created of a large complex data set. In addition to developing the capability of performing animations directly from parallel machines, we are working on innovative approaches at visualizing turbulent flow fields, such as visualizing correlations of fluctuating quantities and visualizing tensor quantities.

Our collaboration with Professor Bajaj has been facilitated by the creation at Purdue of the Center for Computational Image Analysis and Visualization, which is an internally funded multi-disciplinary center to promote collaboration on visualization issues. Our participation in this center will enable us to make better use of the facilities of the APVL.

4 Visualization of Heat Treatment Processes

In cooperation with the NSF and industry sponsored Purdue University Engineering Research Center for Collaborative Manufacturing, we are working on modeling various heat treatment processes. These include developing computational methods for describing the induction heating, quenching and carburizing processes that are used in the surface hardening of steel and aluminum components, such as those found in aircraft frames and engine parts. Several such numerical models have been developed[11-15] which can calculate the temperature, microstructure, stress, and deformation histories during the quenching process, and the carbon content during the carburizing process.

Because these processes are highly non-linear, small changes in one variable, such as microstructure, can have significant impacts on other variables, such as transient stresses. For this reason, it is extremely important to be able to monitor the development of several parameters at once. The capabilities of the *Aerospace Post-Processing and Visualization Lab* have allowed us to make significant improvements in our ability to perceive these subtle interdependencies in process parameters. Using the simulation programs already developed, we are able to store any combination of the time histories of variables of interest to disk. A separate program has been written.which can take this stored information, and display on a single frame contour information for several different variables. Each frame is stored in SGI RGB format, and this procedure is done for any desired number of time steps. These images can then be imported into the IRIS Movie Maker program, which sequences the images into an SGI Movie file that can be saved to video tape through the Galileo system.

We have found these new capabilities useful in two ways. The first is the ability to view a single variable, such as temperature, throughout a quenching cycle. By watching a movie of the temperature history, potential hot and cool spots can be easily detected visually. For a relatively simple geometry, such as the temperature contours of a cylinder during a quench, as shown in Figure 4, the results of a single frame aren't particularly startling, and help to confirm intuition. However after watching a movie of this quench cycle, it can be seen that the temperature at the core of the cylinder actually increases during a portion of the quench, due to latent heat releases during microstructure transformations. This is a phenomena that is extremely difficult to observe through traditional post-processing means, yet is clearly seem from the new methods.

A second capability is to place several contours on a single frame, and observe the evolution of several variables at once, implying their interdependence. Figure 5 shows the temperature and microstructures (pearlite and martensite) for a thin section of a long cylinder. Microstructure evolution is dependent on both temperature and cooling rate. Because it has a large effect on the residual stresses and hardness of the quenched piece, the resulting microstructure is extremely important. The movie that this frame is taken from shows that a thin layer of martensite, which is very hard yet brittle, begins to form at the surface of the cylinder. This is followed by the formation of pearlite, which is more ductile than martensite, in the bulk of the cylinder, and

finally, the martensite transformation at the surface of the cylinder finishes, giving rise to a desirable hardness and stress profile in the piece.

It is the ability to view the evolution of time-dependent simulations that is the greatest benefit of the *Aerospace Post-Processing and Visualization Lab.* By having the ability to watch the interaction of simulation variables on either the monitor or video tape, we are better able to understand the physical mechanisms behind the heat treatment processes. This is of great assistance in our ultimate goal of design of heat treatment processes for obtaining components that meet DoD performance requirements.

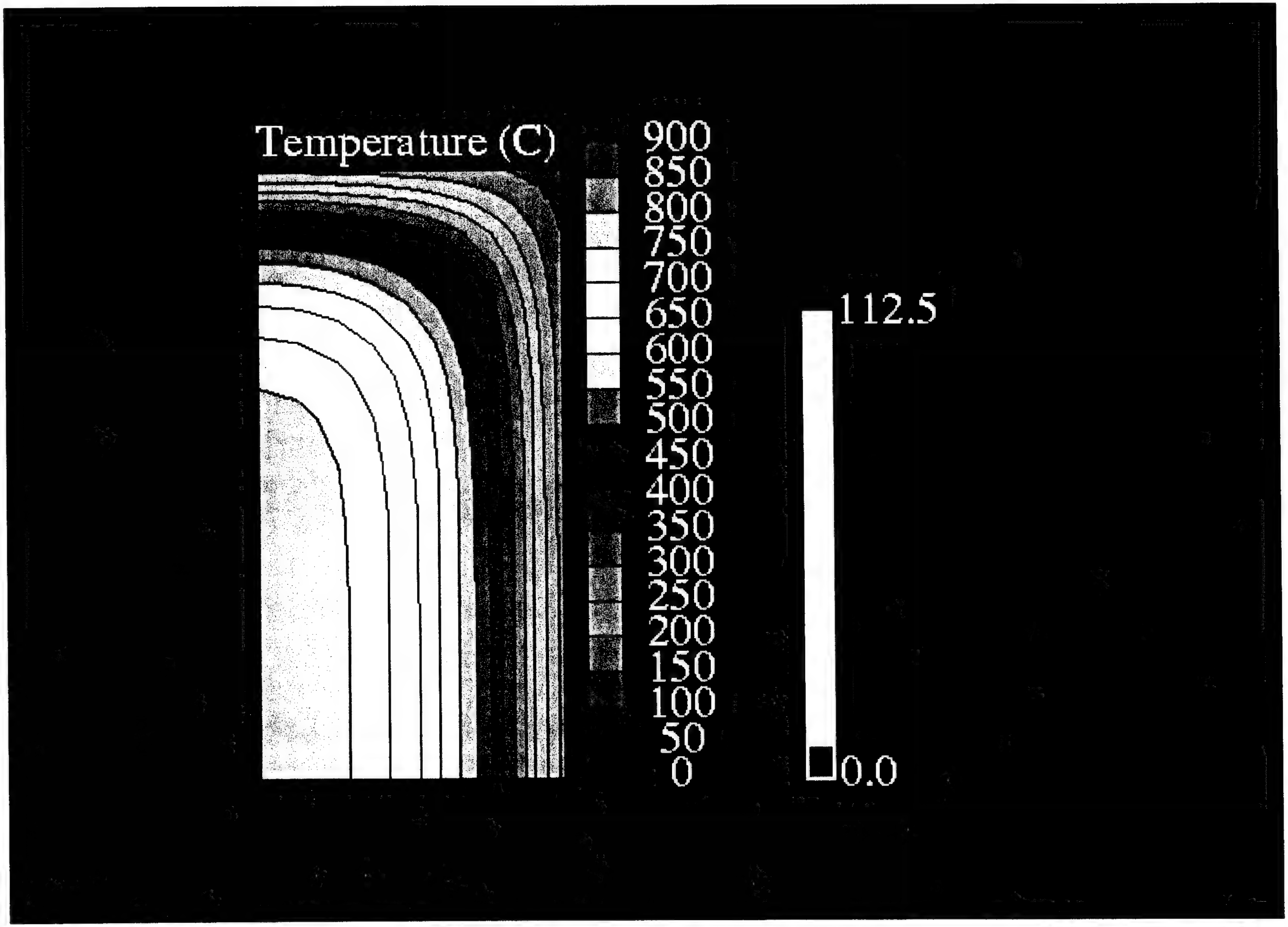


Figure 4: Temperature Contours of a Cylinder During Quenching

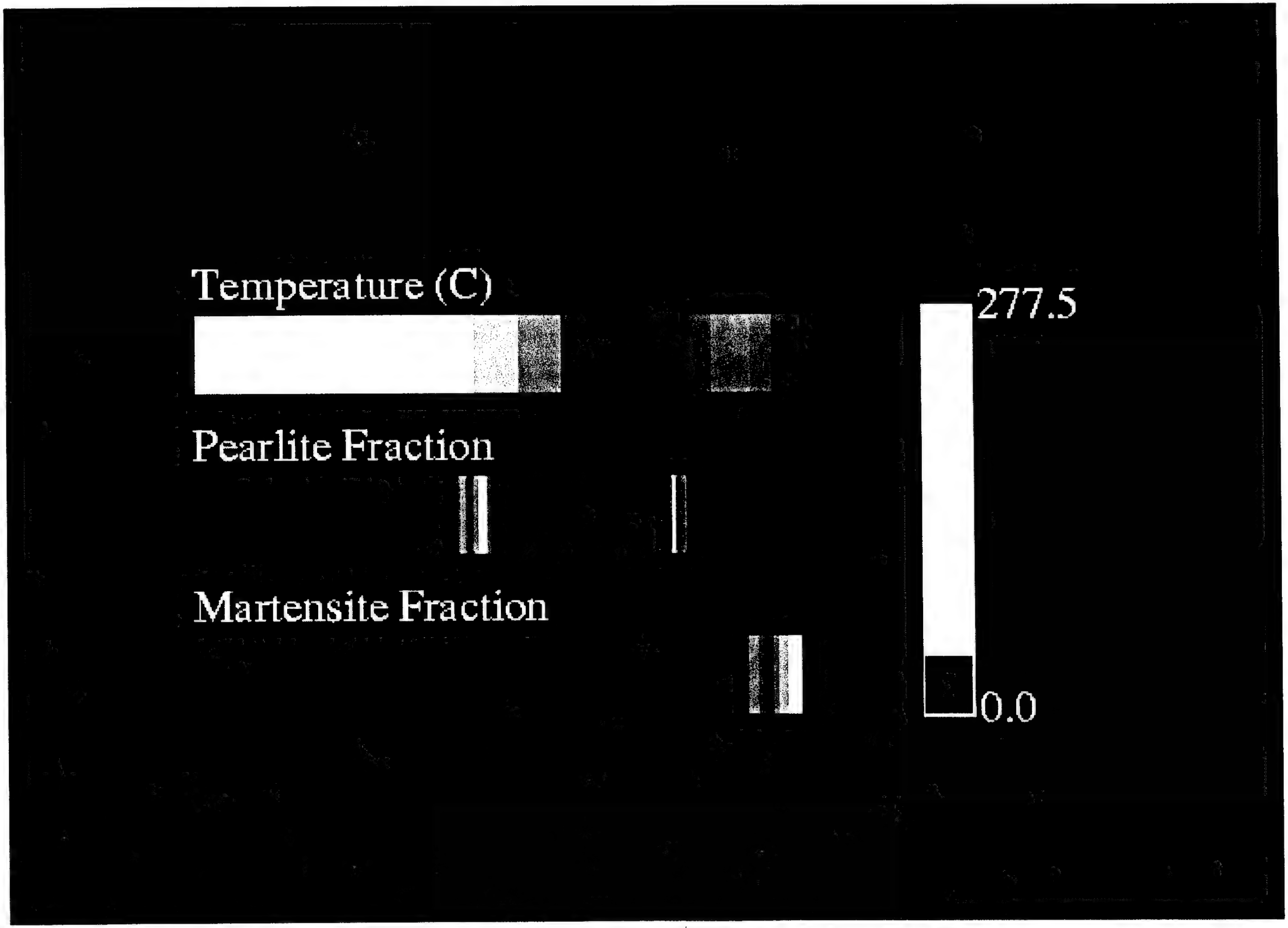


Figure 5: Comparison of Microstructure Evolution with Temperature During Quenching

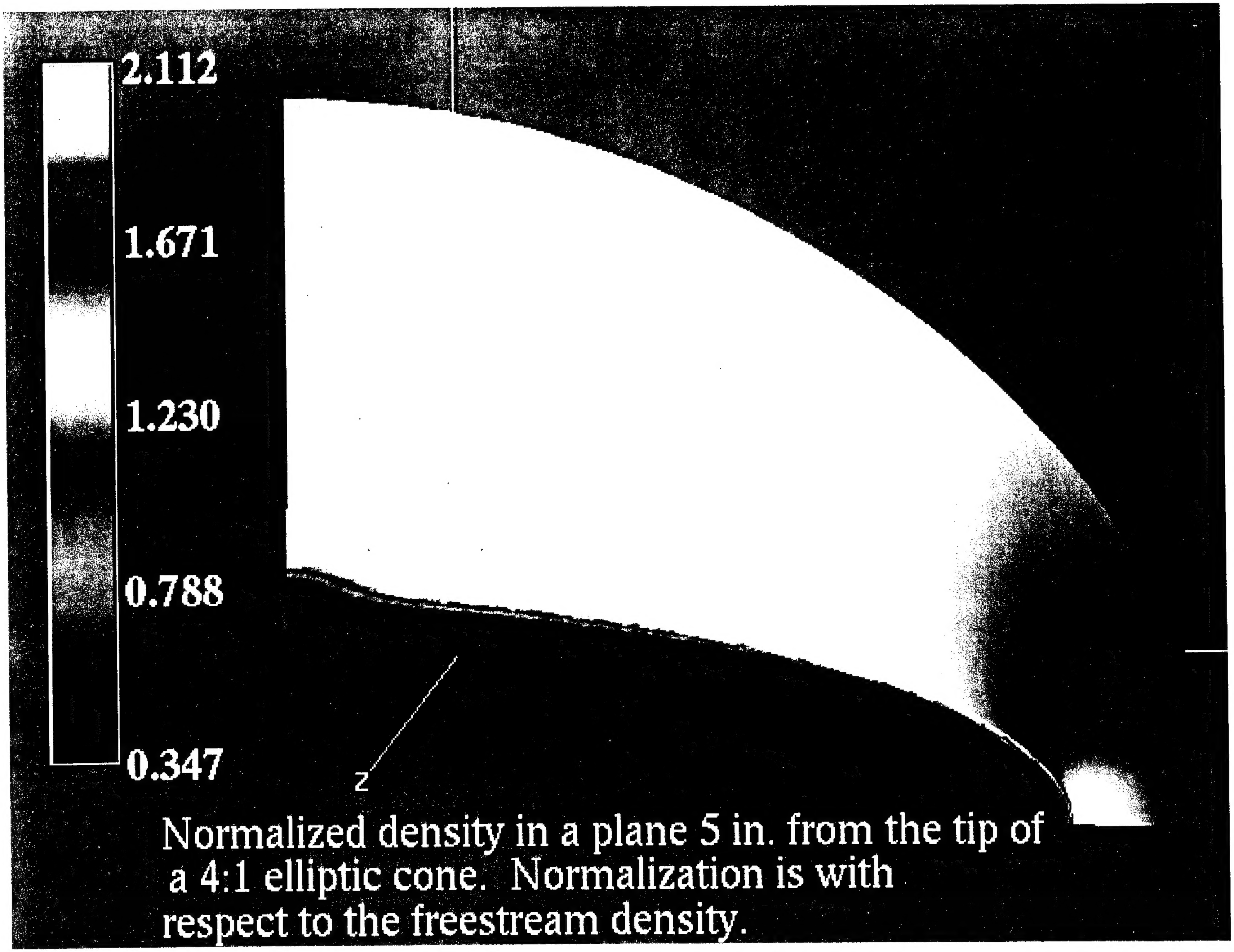
5 Impact on Boundary Layer Transition Program

The DURIP-funded equipment has been used to access computational data provided by Herbert et al.[16] These computations are for the same geometry and flow conditions as those being studied experimentally. The mean-flow results of the computations form a 60 megabyte PLOT3D datafile, which was transferred to Purdue from the authors. However, until Purdue acquired the SGI system under the DURIP, Purdue had no way to access details of these results for comparison to experimental conditions, and for design of experimental apparatus. The plotting package FAST has now been installed on the new SGI machines; this program incorporates PLOT3D and allows us to readily access details of computational results provided by others.

Figure 6 provides an example of the use of these tools in boundary layer transition research. A color contour plot of the density in a plane for one-quarter of the flowfield generated by 4:1 elliptic cone is shown in the figure. Density values are normalized by the freestream density, 0.0323 kg/m3. The cone is 5 inches long with major and minor axes of 1.57 and 0.39 inches. The flowfield was computed by solving the parabolized Navier-Stokes (PNS) equations over the region between the surface of the cone and the shock wave generated by the cone.[16] The computational grid consists of 74 planes in the streamwise direction, each with 56 radial grid lines azimuthally spaced in equal angular increments. Each radial line is composed of 501 grid points. The normalized density is plotted for the plane at the base of the cone, 5 inches from the tip. As seen in the figure, the most compression occurs near the cone major axis where the flow turning angle, and hence the shock wave strength, is greatest. The compression decreases toward the region with the smallest flow turning angle, near the minor axis. Because of the decrease in compression between the major and minor axes, a cross flow is generated from the major axis region to the minor axis region of the cone. The bulge near the surface of the cone on the minor axis is due to the build-up of the boundary-layer on the line of symmetry along the minor axis as the crossflow-induced flow from either side of the cone meets on the line of symmetry.

A single figure like this is of course only the tip of the iceberg. It is now possible for our experimental program to access and use the computational data being obtained by other workers.

It should also be mentioned that the machine stationed at ASL has also been used extensively for a number of other projects. One in particular is a high-lift research program funded by NASA Ames under Grant NAG-1-854. Again, access to an SGI machine that could run the industry-standard codes FAST and PLOT3D was essential to this activity.



Normalized density in a plane 5 in. from the tip of a 4:1 elliptic cone. Normalization is with respect to the freestream density.

Figure 6

6 Conclusions

The creation of *Aerospace Post-Processing and Visualization Lab*, made possible through funding associated with this project, has provided a definite impact on the graphics visualization capabilities within The School of Aeronautics and Astronautics at Purdue University. Interest in the usage of these new capabilities has far exceeded our expectations in developing this lab. Moreover, additional support through funding from *The Boeing Company* and *IBM* has augmented the capabilities of the facility. The creation of these state-of-the-art visualization tools will positively affect future research (both experimental and theoretical) applied to problems of interest to DoD.

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